SOLID STATE PFN CLIPPER STACK ANALYSIS UNDER HIGH PEAK POWER CONDITIONS

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Summary

Previously reported results[1] of a pulse forming network (PFN) end-of-line clipper (EOLC) point out that solid-state diode EOLC stacks are deficient in important pulser requirements; namely stack reverse leakage, forward current rate-of-rise, forward recovery and high forward drop. Some of these deficiencies can be reduced through an improved understanding of silicon diode rectifier operation at high pulsed power conditions. The apparent current rate-of-rise limitation for high pulsed currents and the cause of the apparent phase lag under forward biasing is discussed. The relative contributions of lead inductance, effects of diffusion capacitance, minority carrier transit times and charge storage decay times are reported for two commercial EOLC assemblies. Results of pulser evaluation suggest that improvements can be made in the EOLC design and its operation to reduce inverse voltage appearing at the switch under mis-matched (load-PFN) conditions.

Introduction

High energy, high power pulsers designed and constructed at ERADCOM, Fort Monmouth have utilized metal-ceramic hydrogen thyratrons as switches and capacitors for energy storage. Both these major components are subject to potential degradation if subjected to reverse voltage during operation. Recent experience with ERADCOM's 6 megawatt (MW) average power, (5 gigawatt peak) pulser has shown that the EOLC solid-state clipper diode stacks used to protect the PFN capacitors and switch were adequate for normal operation. When large load mis-matches developed, the diode stacks could not respond quickly enough to prevent internal arcing in the thyratron resulting in a system shut-down. In addition to the slow diode response, the forward drop of the EOLC solid-state diode stack was much higher than anticipated. The transient response of individual stack diodes have been investigated in order to better understand the EOLC behavior. The resistance contribution of the diodes transient forward characteristics impedance was eliminated by forward biasing the diodes. The direct current (dc) forward biasing of the diode allowed the diffusion capacitance to be studied as a function of applied pulsed currents.

Design Considerations for EOL Clipper Circuits

The concept of the EOLC to remove inverse voltage was developed in 1956 by Chatham Electronics and Fort Monmouth Signal Laboratories.[2]

The objective of the EOLC is to remove inverse voltage from the switch tube and the PFN pulse capacitors.

The ideal EOLC stack would have the following performance characteristics:

a. Instantaneous response when switching from reverse bias to forward conduction, or from forward conduction to reverse bias

b. Reverse hold-off far in excess of the highest network operating voltage

c. Very low forward drop (less than 200 volts)

d. Very low reverse leakage (less than 500 microamperes (μA)

e. Negligible reactance (zero lead inductance

f. Capable of pulsed current in excess of 50 kiloamperes for tens of microseconds (μs)

g. Compact and lightweight

h. Identical diode characteristics eliminating the need for snubber compensation.

Practical design considerations of ERADCOM for its MW pulsers are the following:

1. The clipper stack shall not fail under the worst-case conditions

2. The EOLC voltage safety factor shall be 1.5 (maximum stack hold-off divided by maximum, normal PFN voltage)

3. The current safety factor shall be greater than 3 (maximum single pulse current divided by maximum normal stack operating voltage)

4. The EOLC stack inductance and stack snubber capacitance shall be as small as possible and the snubber resistor values as high as practical.

5. The reverse to forward recovery time shall be less than 1 μs for pulse widths in the order of 10 μs.

Figure 1 is a simplified description of the pulser circuit. The EOLC circuit consists of a low inductance, high power resistive load and the solid-state diode stack. The resistor value was chosen to match the impedance of the PFN and its dissipative capacity was selected to handle the worst-case condition of a shorted pulser load at full power for the time it takes the system to cease operation and discharge its stored energy. The EOLC stacks are also designed for worst-case conditions, that is, the stack must handle the highest PFN over-voltage in the reverse bias direction and safely conduct full short circuit current where both the pulse load and clipper loads are shorted for the duration it takes to shut down the pulser.

The trade-off in EOLC stack design is in the choice of diode size. Small, fast diodes will switch rapidly, do not require individual diode snubber protection, however they can not survive high (< 5kA) forward currents. Parallel-series combinations of 6 ampere (average current rating) diodes are used in commercially available high voltage stacks such as

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Semtech's model SA 5717 which are rated for 4 kiloamperes of forward current and 60 kilovolts (kV) of reverse hold-off.[3] Each diode in the Semtech stack has a reverse hold-off of 1 kV.

For the 6 MW pulser with its 40 kiloampere/single section maximum operating current and 40 kV maximum PFN voltage would require 2400 individual diodes if the design were to follow ERADCOM design principles. This large number of diodes would result in appreciable lead inductance and the benefits of fast recovery would be negated, in part, by the effective capacitance of all the diodes.

Large diodes are slower, have appreciable capacitance in the forward and reverse directions and require snubber resistors and capacitors to insure proper voltage division in series stacks. They also have high current capacities and high voltage hold-off. Large diode stacks are commercially available and two such designs will be discussed in this paper. The first stack assembly,[4] Figure 2, consists of 3 stacks (Westinghouse 5H19B11Z2041AP) in series. One stack assembly for each PFN or two assemblies per switch. Each stack consists of 20 each 1N4594 diodes with a 30 kilohm, 10 watt (W) resistor and a 0.1 microfarad (μF), 1 kV dc capacitor across each diode. This EOLC design requires 60 diodes. Each diode have a 1,000 volt repetitive peak reverse voltage and a 150 ampere maximum continuous forward current. A second stack, Westinghouse (HH 176B2811AA-SPL)[5] consisted of 20 diodes in series, each capable of 200 amperes continuous forward current and 2800 volts repetitive peak reverse voltage (also in Figure 2). Each diode had a 30 kilohm, 35 W resistor and a 0.01 μF capacitor for its snubber circuit. The two EOLC assemblies were evaluated in a ERADCOM MW pulser. The first stack had been evaluated in an earlier paper against a pair of Kuthe 7890 hydrogen thyratrons in parallel. The results of that study was that the gas clipper exhibited a lower forward drop, higher clipper current with no phase difference between the increasing inverse PFN voltage and the rising clipper current. The following discussion of individual diode performance employed diodes taken from the two stack designs.

Diode Performance

Diode voltage was measured by two probe method as shown in Figure 3a. One probe detects diode voltage plus a pick-up voltage which corresponds to the rate of change of $(\overline{B}.d\overline{A})$, where B is the magnetic field intensity due to the diode current and $d\overline{A}$ corresponds to the element area formed by the two leads of the detecting probe and the body of the diode. The second probe, referred to as the compensation signal geometrically has a loop area equal to dA and is in the same plane relative to the stripline as the diode voltage signal pick-up. This probe also detects the rate of change of $\overline{B}.d\overline{A}$ produced by the diode current.

By proper oscilloscope differential preamplifier settings a true diode voltage was obtained as shown in Figure 3b. Figure 4 verifies the technique by illustrating the compensation signal subtracted from the diode signal for a shorted diode. The resulting voltage wave form mirrors that of the current wave form as expected.

1. General Diode Behavior

In the experiments with very large current pulses (30 kA), the injection level of holes into n-region is very high. This leads to a formation of a very large diffusion capacitance. The following phenomena were observed with diodes operating in excess of 1 kiloampere of pulsed current:

1) charge carrier transit time,
2) diffusion capacitance, and
3) effect of a dc bias on the diode voltage.

The diode voltage was monitored by the two probe method and the current by a current transformer. The results were stored on a Tektronix 7834 oscilloscope. Figure 3b shows the voltage and current waveforms on a time scale of 2 μs per division for a Westinghouse R600 diode. The forward conduction pulse is preceeded by a one second period of zero applied voltage. The voltage trace consists of a fast spike of approximately 0.5 μs followed by a slowly decaying diode voltage dropping to zero at the end of the current pulse. Closer examination of the two waveforms reveals a 25 nanosecond (ns) delay in the rise of diode current (Figure 5). The diode forward voltage spike consists of a combination of resistive drop across the base (n-region) plus the charging voltage of the diffusion capacitance. The fast fall of the spike corresponds to the charge storage decay and the remaining slowly falling voltage results from ambipolar diffusion limiting the extraction rate of the large population of injected charge carriers.

2. Transit Time

Transit time[6] is defined as the time it takes the minority carriers to cross the diode base region. Even though the diodes studied were wide based diodes it would be reasonable to assume that some of the carriers reached the metallic contact due to the excessive injection rate. A time of approximately 25 ns can be seen in Figure 5 where the diode voltage has already begun increasing before the minority carriers have crossed the base and a current is observed in the external circuit.

3. Charge Storage Time and Diffusion Capacitance

Diffusion capacitance is principally due to the injection of charge (minority carriers) in the p, n-region. It is given by:[7]

$$C_{diff} = K\tau_p \frac{q}{kT} I_E$$

Where $\tau_p \simeq$ hole recombination time of minority carriers in the n-region $\simeq .2\mu s$ and $K \simeq 1$.

The diffusion capacitance is proportional to the applied current I_E. Since I_E is $\simeq$ 30 kA, C_{diff} is very large $\simeq 10^{-3} F/cm^2$. This has been observed from the relationship between the increasing voltage spike and the increasing magnitude of the applied current pulse. The effect of diffusion capacitance can be seen in Figure 6. The initial voltage rise corresponds to the voltage drop across the neutral n-region. Subsequent increase and decay of voltage signal corresponds to the changing and discharging of diffusion capacitance.

Charge storage time constant can be found from the decay of the voltage across the diode resistance. A time constant of 0.2 μs can be obtained from Figure 6.

The maximum voltage corresponds to the voltage

across the resistance of the n-region plus the contact resistance.

The reduction of the peak of the voltage was established by dc biasing the diode. This is seen in Figure 7 where 0.37 ampere biasing current is used. However a bias current of 1 to 15 amperes did not show any discernible change in reduction of the peak voltage.

The reduced voltage spike accomplished by applying a dc bias, is a result of lowering the initial dynamic resistance of the diode (Figure 8) prior to applying the high current pulse. For currents below 1A the spike shows dependence on the dc bias current; this is equivalent to bypassing of a large C_{diff} by a leakage resistor.

Diffusion capacitance effect and a 2 μs time constant of voltage decay is shown in Figure 9.

4. High Forward Voltage Drop at Kiloampere Pulsed Currents

The forward voltage drops and companion current traces for the larger diode are shown in Figures 10a and 10b for 400 and 12,500 amperes of peak currents. In the region beyond the spike the forward voltage decays with a characteristic time constant of 2 μs independent of pulsed currents from 600 to 30,000 amperes whether the diode is biased or not (Figure 9, Figure 10). This voltage decay results from the plasma in the n-region generated by the high injection rate. The excess holes are extracted at the contact at a rate controlled by ambipolar diffusion. Device performance is similar to the subregime found in TRAPATT diodes.[8] At lower peak currents, the tail of the forward voltage trace follows the current (Figure 10b). This follows the published forward current vs. forward voltage characteristics for these type of diodes.[9]

5. Inductive Effects of Leads

The 1N4594 diodes used in the first Westinghouse stack design (SH 19B11Z2041AP) had a lead inductance of 14 nanohenries which contributed an inductive voltage spike typically ten times the voltage across the diode itself. At 30 kiloamperes the forward drop due to inductance was 400 volts. The larger diode used in the second stack design (Westinghouse HH 176B2811AA-SPL) had shorter leads and the inductive voltage spike was reduced by a factor of 2.

EOL Stack Assembly Performance

The EOL stack assemblies and the EOL clipper load were connected to the end of the PFN line as shown in Figure 1. The PFN load was shorted by clamping the ends of the PFN load stripline together at the load end. Opposed diodes were installed in the ground return of the stripline which provided a comparison of diode and EOL clipper stack performance. The PFN short-circuit current was monitored by a Pearson 1000 ampere per volt current transformer (Model 2665). The load and clipper currents were varied from 2000 A peak to 30,000 A peak by varying the charging voltage, E_{bb}. Two Tektronix P6015 20 kV, 1000X voltage probes were mounted at either end of the EOL stack assembly and another Pearson 1000 A per volt current transformer (Model 2665) monitored clipper current. The two voltage probes were connected to a second Tektronix 7834 scope preamplifier, a 7A26 operated in differential mode.

The results of the peak inverse voltage appearing across the EOL diode stack for the two stack designs are plotted in Figure 11. At a clipper current of 25 kiloamperes the old stack design has 2.4 times the peak inverse voltage as compared to the new stack design, even though the smaller diode has lower voltage drop at all times. This improved performance indicates the larger diode with their higher repetitive voltage hold-off reducing the number of diodes required, should allow for more reliable pulser operation. Another factor in favor of the new stack design is the lower inductance of the stack design with its shorter diode leads. The long flying lead of the 1N4594 diode could account for its much higher initial peak forward drop.

Based on the results of individual diode performance it is apparent that stack inductance predominates in the 20 diode stack version. The apparent lag of stack current results from the transient behavior of large diodes conducting in the forward direction at kiloampere pulsed currents. To overcome this limitation there is a possible approach. The most obvious approach would be to relocate the PFN connection for the EOLC somewhere just short of the end of the PFN line. This distance would be chosen to advance the application of inverse PFN voltage so that for the time it takes the inverse voltage to move pass the EOLC connection, reach the end of the PFN line, reflect back to the EOLC connection, the stack would have time to be in a full conduction mode. Then the stack forward voltage would have decreased to 200 volts as required for proper clipper operation.

Conclusions

The inherent limitations of forward recovery time makes the solid-state approach, as it presently stands, less than ideal. If the forward recovery limitations were not present, then the solid-state approach would be more attractive as the forward voltage drops of the diodes are typically 10 to 15 volts for kiloampere pulsed currents. Inductive diode leads should be eliminated in stack designs. The need for snubber circuitry should be eliminated through matching of individual diodes comprising each EOLC assembly. Diode redesign to speed-up diode response would improve performance. Biasing the diode with 10 milliamperes or more of forward current will reduce spiking of the diode forward voltage on turn-on. Connecting the clipper stack and its clipper resistor to the PFN somewhere before the EOL could compensate for the delay of diode turn-on.

Presently diode stacks as EOLC can only be applied if the pulse width of the pulsed current is larger than 5 μs, or else the diodes will never have a chance to turn-on. For fast pulsers at high currents only a gas-filled clipper tube will protect the thyratron switch or the PFN capacitors from reverse voltage spikes associated with load mismatches.

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